TECHNICAL NOTES

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

No. 672

FLOW OBSERVATIONS WITH TUFTS AND LAMPBLACK OF

THE STALLING OF FOUR TYPICAL AIRFOIL SECTIONS

IN THE N.A.C.A. VARIABLE-DENSITY TUNNEL

By Ira H. Abbott and Albert Sherman
Langley Memorial Aeronautical Laboratory

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE NO. 672

FLOW OBSERVATIONS WITH TUFTS AND LAMPBLACK OF

THE STALLING OF FOUR TYPICAL AIRFOIL SECTIONS

IN THE N.A.C.A. VARIABLE-DENSITY TUNNEL

By Ira H. Abbott and Albert Sherman

SUMMARY

A preliminary investigation of the stalling processes
of four typical airfoil sections was made over the criti-
cal range of the Reynolds Number. Motion pictures were
taken of the movements of small silk tufts on the airfoil
surface as the angle of attack increased through a range
of angles including the stall. The boundary-layer flow
also at certain angles of attack was indicated by the pat-
terns formed by a suspension of lampblack in oil brushed
onto the airfoil surface. These observations were analyzed
together with corresponding force-test measurements to de-
rive a picture of the stalling processes of airfoils.

INTRODUCTION

The stalling characteristics of an airfoil section
are among its most important aerodynamic properties, not
only because the value of the maximum lift coefficient
determines the wing loading permissible for a given stall-
ing speed but also because these characteristics influence
the manner of stall of tapered wings, which is intimately
connected with lateral stability and damping in roll at
the stall. A discussion of the mechanism of the stall is
given in reference 1, in which the stall is considered to
be caused by laminar or turbulent separation resulting in
general flow breakdown; the type of separation is governed
by the airfoil section and the Reynolds Number and is in-
fluenced by the general boundary-layer conditions. Al-
though much experimental and theoretical study has been
devoted to the mechanism of the stall, the phenomena which
occur are so complex that the understanding of the subject
remains unsatisfactory.

The present preliminary investigation was undertaken
to study the stalling of four typical airfoil sections
over the critical range of the Reynolds Number in the
N.A.C.A. variable-density tunnel. This investigation is
to be extended to include the stalling of tapered wings
in the N.A.C.A. variable-density tunnel and of airfoil
sections in flight and in wind tunnels of much less tur-
bulence than that of the N.A.C.A. variable-density tunnel.
It is expected that the results of these investigations,
together with advances in boundary-layer theory, will
provide some additional information leading to a better
understanding of the nature of the stall and of the ef-
fects of wind-tunnel turbulence on airfoil data.

Motion pictures of the movements of small silk tufts
on the airfoil surface were made as the airfoil passed
through the stall. As an indication of the boundary-layer
flow, patterns formed by a suspension of lampblack in oil
brushed onto the airfoil surface were observed at certain
angles of attack. These observations were correlated with
force-test measurements to provide a partial picture of
the stalling processes of the airfoil sections under the
flow conditions of the variable-density wind tunnel.

METHOD

The models employed were the N.A.C.A. 0009 and 8318
rectangular, square-tip airfoils and the N.A.C.A. 0012 and
4412 rectangular, rounded-tip airfoils. The tests were
similar to the usual force tests (reference 2) except that
two angle-of-attack stings instead of the usual single
sting were used to eliminate interference at the midsec-
tion of the airfoil. The only force measurements made
were readings of the lift coefficients near the stall.

For the observations of the general flow above the
airfoil surface, fine silk tufts were employed; their
length and spacing were of the order of 1/4 inch. They
were affixed by their front ends to the airfoil upper sur-
face near the midsection and their positions were stag-
gered to minimize mutual interference. A remotely oper-
ated 16-millimeter motion-picture camera was used to take
the picture records, the tunnel lights being dimmed momen-
tarily at specified values of the continuously increasing
angle of attack to indicate the angle of attack on each
film.

For the boundary-layer patterns, lampblack was sus-
pended in oil of various viscosities, the viscosity being
changed to suit the tunnel operating conditions, and was
brushed onto the airfoil in as thin a film as possible.
The observations were made at fixed angles of attack to
obtain patterns of the flow for steady conditions. Motion-
picture records, supplemented by visual observations when
possible, were obtained of the formation of the patterns.
Position measurements of the prominent lines and regions
in the lampblack patterns were obtained after each run.
Although some features of most of the patterns changed
slowly with time after the air flow was stopped because
the oil ran over the surface, it is believed that these
measurements represent the pattern with a fair degree of
accuracy.

The tufts were expected to describe the general flow
over the airfoil, and the lampblack in oil was expected
to indicate the nature of the flow in the boundary layer.
It is important to recognize the possibility that the
tufts or the lampblack may have changed the character of
the flow by their presence. This effect, however, is be-
lieved to have been small, inasmuch as the values of the
maximum lift coefficients agreed with the values previously
obtained without tufts.

RESULTS AND DISCUSSION

Figures 1 to 4 present the results of the tuft obser-
vations correlated with the corresponding section lift
curves derived from force-test data. The flow representa-
tions are grouped in columns corresponding to the differ-
ent values of the effective Reynolds Number R_e; the ordi-
nate position of each representation corresponds to the
section angle of attack α_0. Important features of the
flow in the boundary layer as deduced from the lampblack
patterns are indicated on the figures by appropriate sym-
bols. Where symbols are lacking, no measurements were
made.

Interpretation of data.- In the interpretation of the
tuft observations, the two conditions termed "unseparated"
and "fully separated" flow were easily distinguishable.
For unseparated flow, the tufts would ordinarily lie flat
on the airfoil surface without movement; for separated
flow, the tufts fluctuated violently in direction, some-

times disappearing entirely from the pictures but general-
ly indicating a strong reversed flow. The details of the
transition from unseparated to fully separated flow varied
with the different airfoils and with the values of the
Reynolds Number.

In some cases, such as for the N.A.C.A. 4412 airfoil,
the first fluctuations of the tufts as the angle of attack
of the airfoil was increased were small uncertain movements
of those nearest the trailing edge. Such movements were
considered to be caused by the relatively thick turbulent
boundary layer, and the flow is considered to be unsepa-
rated.

In other cases, the first movements of the tufts were
sudden, violent flicks in which the flow indicated by the
tufts completely changed direction. These flicks might
occur over either a small or a large region. Sometimes
these flicks were of very short duration, occurring only
for the length of time required for the air to travel two
or three chord lengths. As the angle of attack increased,
these flicks commonly became more frequent and of longer
duration. The flow in this case is represented in figures
1 to 4 as "momentarily separated."

As the flicks became more frequent and of longer dura-
tion, a point was reached where the time during which the
flow was separated was of the same order as the time of
unseparated flow. Such a condition is defined as being
"intermittently separated." This condition often occurred
without the intervention of the sudden short flicks pre-
viously mentioned.

In the case of the lampblack-in-oil observations,
study of motion-picture records and visual observation in-
dicated that the first movements of the very thin film
usually consisted of a downstream flow from the leading
edge and a cleaning out of the film by both upstream and
downstream movements from some point downstream from the
location of the peak negative pressure. In the interme-
diate region, two sharp lines of lampblack and oil devel-
oped. These lines might either be merged or be separated
by an appreciable distance, in which case the film between
them remained undisturbed by the flow. In all cases, the
distance between the first sharp line and the downstream
point from which the film moved in both directions de-
creased at increased Reynolds Numbers or reduced angles of
attack, the entire pattern disappearing at sufficiently

low angles. The distance between the two sharp lines
varied accordingly. The general appearance of a pattern
is shown in figure 5. The sketch (fig. 5a) points out the
most definite features usually observed in a lampblack
pattern as they occurred on the N.A.C.A. 8318 airfoil.
(See fig. 5b.) Before the photograph (fig. 5b) was taken,
incidentally, the pattern had run appreciably, losing its
original sharpness.

The proper interpretation of such patterns is doubt-
ful, but the variations of the pattern with angle of at-
tack and Reynolds Number correspond closely to what would
be expected from consideration of the boundary-layer con-
ditions on the basis of the following tentative interpre-
tation.

The first, or upstream, sharp line is thought to be
associated with a local reduction in the shearing forces
at the surface of the airfoil. Such a reduction in the
shearing forces may be caused by laminar separation and,
for brevity, the location of this line will be referred to
as "point of laminar separation." The point from which
the film moved in both the upstream and the downstream di-
rections is considered to be the point where the flow re-
turns to the surface as the result of the formation of
turbulence. The second sharp line then becomes the up-
stream limit of the region of strong reversed flow under
the overrunning boundary layer.

On the basis of this interpretation, the patterns
show the increased difficulty experienced by the flow in
returning to the surface after laminar separation at high
angles of attack or at low values of the Reynolds Number.
Eventually this process, in the case of the N.A.C.A. 0009
and 0012 airfoils, leads to complete flow separation from
near the leading edge, as indicated by the tuft observa-
tions. In the case of the N.A.C.A. 4412 and 8318 airfoils,
the stall occurs by progressive separation from near the
trailing edge before the laminar separation becomes suffi-
ciently severe to cause complete flow breakdown.

The positions of the first sharp line of the patterns
are tabulated in table I together with some theoretical
separation points computed for the same conditions by the
method of reference 3. The most important features of the
boundary-layer flow, as indicated by the foregoing inter-
pretation, are shown in figures 1 to 4. Some features have
been omitted from the presentation because of difficulty in

measuring or interpreting the patterns. In particular, the
point where the flow is considered to return to the surface
is often omitted because too little lampblack remained in
this region to permit measurement after the pattern was
formed. On account of these difficulties and the possibil-
ity that the accumulation of the lampblack may affect the
flow, the use of this method for the study of the boundary
layer is not advocated.

N.A.C.A. 0009 airfoil.- The results for the N.A.C.A.
0009 airfoil are presented in figure 1. This airfoil is
an example of the type in which the stall is influenced
primarily by the laminar separation occurring near the
leading edge. In the lower critical range of the Reynolds
Number, the first evidence shown by the tufts of the ap-
proaching stall is momentary separation occurring at the
leading edge followed by intermittent separation either
spreading downstream from the leading edge or occurring
simultaneously over the whole upper surface. The com-
pletely separated region grows backward to cover the en-
tire upper surface. If the lift is sufficiently low, how-
ever, it continues to increase to about the maximum lift
coefficient for a flat plate.

At a value of the effective Reynolds Number of
3,400,000, the action is similar to that in the lower
range except that momentary separation first occurs near
the trailing edge, which probably indicates separation of
the turbulent boundary layer. The separated region does
not grow forward but probably influences the momentary
separation that suddenly occurs over the entire upper sur-
face; the stall then develops much the same as at the
lower values of the Reynolds Number. At the higher values
of the Reynolds Number, intermittent separation occurs
simultaneously over the entire upper surface.

N.A.C.A. 0012 airfoil.- At the lower end of the criti-
cal Reynolds Number range, the stalling process for the
N.A.C.A. 0012 airfoil (fig. 2) is similar to that for the
N.A.C.A. 0009 airfoil, in that separation grows back from
the leading edge to cover the entire upper surface and then
increases in intensity with increasing angle of attack. At
the higher Reynolds Numbers in the critical range, the sep-
aration starts at the trailing edge and probably influences
the complete flow breakdown from the leading edge that oc-
curs at larger angles of attack.

N.A.C.A. 4412 airfoil.- The characteristics of the

stalling process for the N.A.C.A. 4412 airfoil (fig. 3)
appear to be opposite to those for the N.A.C.A. 0009 air-
foil. Separation grows forward from the trailing edge
with increasing angle of attack, evidently as a result of
progressive separation of the turbulent boundary layer.
Separation originates at lower angles of attack as the
Reynolds Number is increased and the stalling process
covers a larger range of angles, the maximum lift coeffi-
cient being higher at the higher values of the Reynolds
Number. There are no sudden changes in the character of
the flow in the region of the stall. The overrunning flow
appears to be unaffected by the laminar separation indi-
cated by the lampblack tests, but the presence of this
laminar separation probably influences the turbulent sep-
aration near the trailing edge. (Compare reference 1.)

N.A.C.A. 8318 airfoil.- Figure 4 shows the stalling
processes for the N.A.C.A. 8318 airfoil, which are some-
what similar to those for the N.A.C.A. 4412. At a value
of the effective Reynolds Number of 200,000, a sudden sharp
drop in lift occurs at the maximum and is accompanied by a
corresponding sudden change in the character of the flow.
At all values of the effective Reynolds Number for which
tests were made, except for a value of 800,000, the tufts
showed separation phenomena at the middle of the section
corresponding roughly with the region of reversed flow in-
dicated by the lampblack at the lower values of the Reynolds
Number. In general, however, the stall results from pro-
gressive separation of the turbulent boundary layor, the
separated region growing forward from the trailing edge.
The leading edge resists the process of separation much
more markedly than does that of the N.A.C.A. 4412.

General stalling processes.- The stalling processes
shown by these tests are in agreement with the discussion
of stalling presented in reference 1. The final flow
breakdown occurs either as leading-edge separation, caused
by separation of the laminar boundary layer and failure to
reestablish the flow through the formation of turbulence,
or as separation of the turbulent boundary layer near the
trailing edge. These two stalling processes are not, how-
ever, separate phenomena occurring independently but are
intimately related, the actual point of separation and its
growth being influenced by the general boundary-layer con-
ditions.

When separation occurs near the leading edge (figs. 1
and 2), it usually causes a sudden drop in lift either with

or without violent fluctuations between the two conditions
of stalled and unstalled flow. In the case of the N.A.C.A.
0009 airfoil (fig. 1), this type of separation occurred at
all values of the Reynolds Number; but, at the lower values,
the flow was partly reestablished over a large portion of
the chord and the stall was progressive. The reestablish-
ment of the flow was facilitated by the low lift coeffi-
cient at the stall, which indicates relatively low adverse
pressure gradients.

When separation occurred near the trailing edge (figs.
3 and 4), it progressed forward without any sudden flow
changes or drops in the lift except in the case of the
N.A.C.A. 8318 airfoil at the lowest value of the Reynolds
Number tested, for which the final flow breakdown apparent-
ly occurred as the result of forward separation.

The question arises as to the extent to which the
general flow is separated and to which the lift is affect-
ed when separation is shown by the tufts on the surface,
particularly when the separation shown by the tufts is of
short duration. In the present tests, the tufts often
failed to show the local separation indicated by the lamp-
black, which indicated that the region of reversed flow
was very shallow and had little effect on the general flow.
Similarly, less shallow regions of reversed flow might be
indicated by the surface tufts but have little effect on
the lift coefficient. Jones (reference 4) studied the flow
by means of tufts attached to small rods extending some
distance from the airfoil surface, but little has been done
to correlate the results of such studies with the effects
on instantaneous lift for particular airfoil sections. Fur-
ther study of the detailed flow changes and the accompany-
ing fluctuations of the forces at the stall appears to of-
fer a promising field of research leading to a better un-
derstanding of the effects of scale and turbulence as well
as of the effect of the type of stall on airplane perform-
ance.

Langley Memorial Aeronautical Laboratory,
    National Advisory Committee for Aeronautics,
        Langley Field, Va., September 7, 1938.

REFERENCES

1. Jacobs, Eastman N., and Sherman, Albert: Airfoil Sec-
      tion Characteristics as Affected by Variations of
      the Reynolds Number. T.R. No. 586, N.A.C.A., 1937.

2. Jacobs, Eastman N., and Abbott, Ira H.: The N.A.C.A.
      Variable-Density Wind Tunnel. T.R. No. 416,
      N.A.C.A., 1932.

3. Von Kármán, Th., and Millikan, C. B.: On the Theory
      of Laminar Boundary Layers Involving Separation.
      T.R. No. 504, N.A.C.A., 1934.

4. Jones, B. Melvill: Stalling. R.A.S. Jour., vol.
      XXXVIII, no. 285, Sept. 1934, pp. 753-769.

TABLE I

Theoretical and Measured Laminar Separation Points

(Measured points obtained from lampblack patterns)

N.A.C.A. airfoil	R_e (millions)	α_0 (deg.)	c_l	Laminar separation points (percent of chord from leading edge)	
				Theoretical	Measured
0009	0.4	6.2	–	–	0.5
	6.1	11.0	1.080	0.3	.3
	8.2	11.0	1.080	.3	?
0012	.4	6.3	–	–	3.2
	.4	9.6	–	–	1.0
	.4	11.6	–	–	.5
	1.7	9.4	.910	1.6	1.3
	1.7	11.1	1.050	1.2	1.0
	1.7	11.9	1.100	1.2	.5
	3.4	9.4	.910	1.6	1.4
	3.4	14.2	1.339	.8	.4
4412	.4	10.3	–	–	1.6, 1.4
	1.7	10.2	–	–	1.2
	3.4	13.5	–	–	.9
8318	.2	8.3	–	–	21.5
	.4	8.0	1.420	22.6	21.6
	.8	8.0	1.445	22.1	26
	1.7	8.0	–	–	None
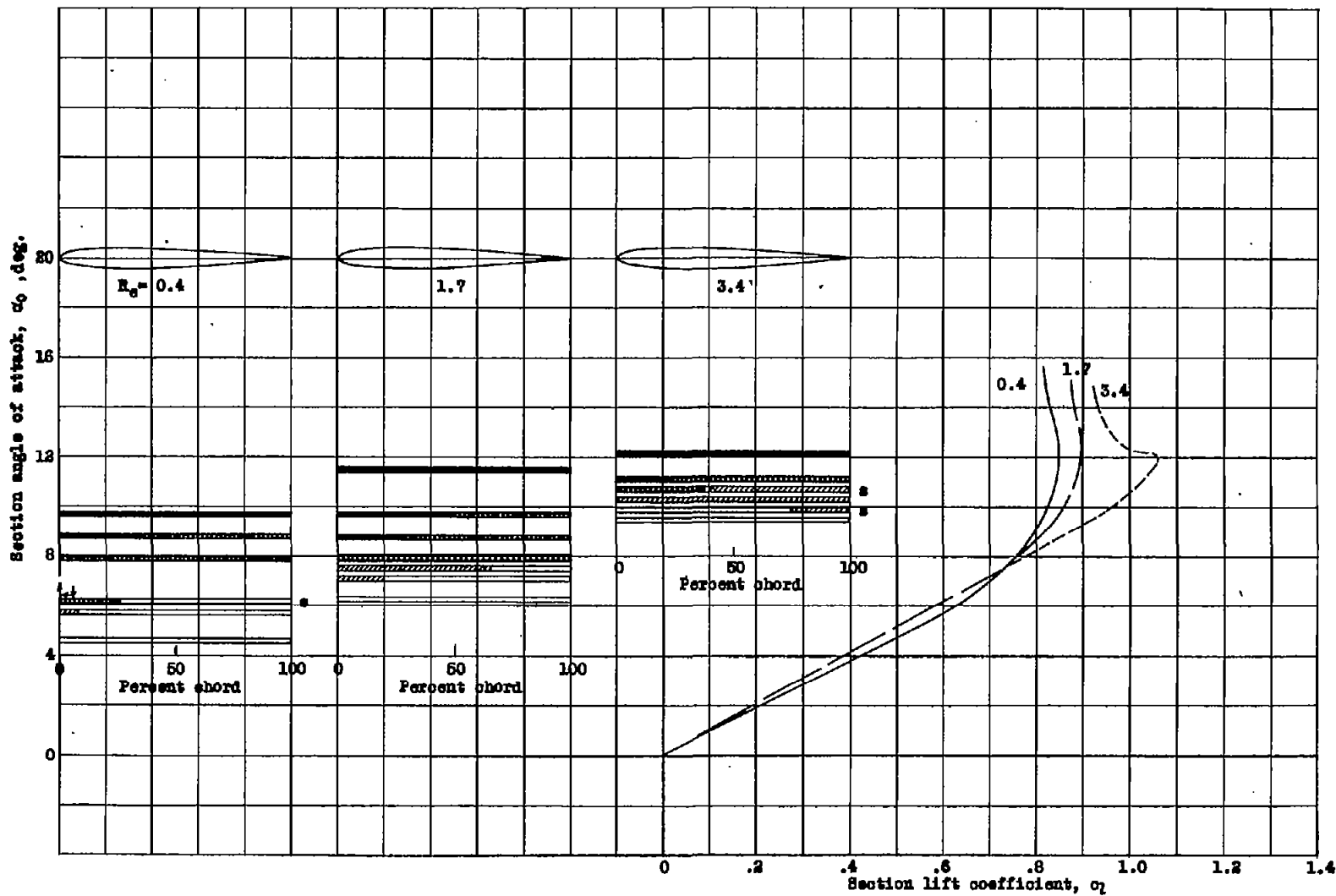
Figure 1a.– Flow observations on the N.A.C.A. 0009 airfoil. (See figure 1b for key)

Section angle of attack, α_o, deg.

28

24

20

$R_o=6.1$

8.2×10^6

16

6.1

8.2

12

s

s

s

s

s

50

100

0

50

100

Percent chord

Percent chord

8

4

0

Key for 1a and 1b
Tuft observations of the flow
over the airfoil upper surface.

Unseparated flow.

Momentarily separated.

Intermittently separated.

Separated.

s   Sudden establishment of new
state of flow.

Lampblack-in-oil observations.

Point of laminar separation.

Point of reestablished flow.

Region of reversed flow.

0   .2   .4   .6   .8   1.0   1.2   1.4   1.6   1.8   2.0   2.2

Section lift coefficient, c_l

Figure 1b.- Flow observations on the N.A.C.A. 0009 airfoil.

Fig. 2
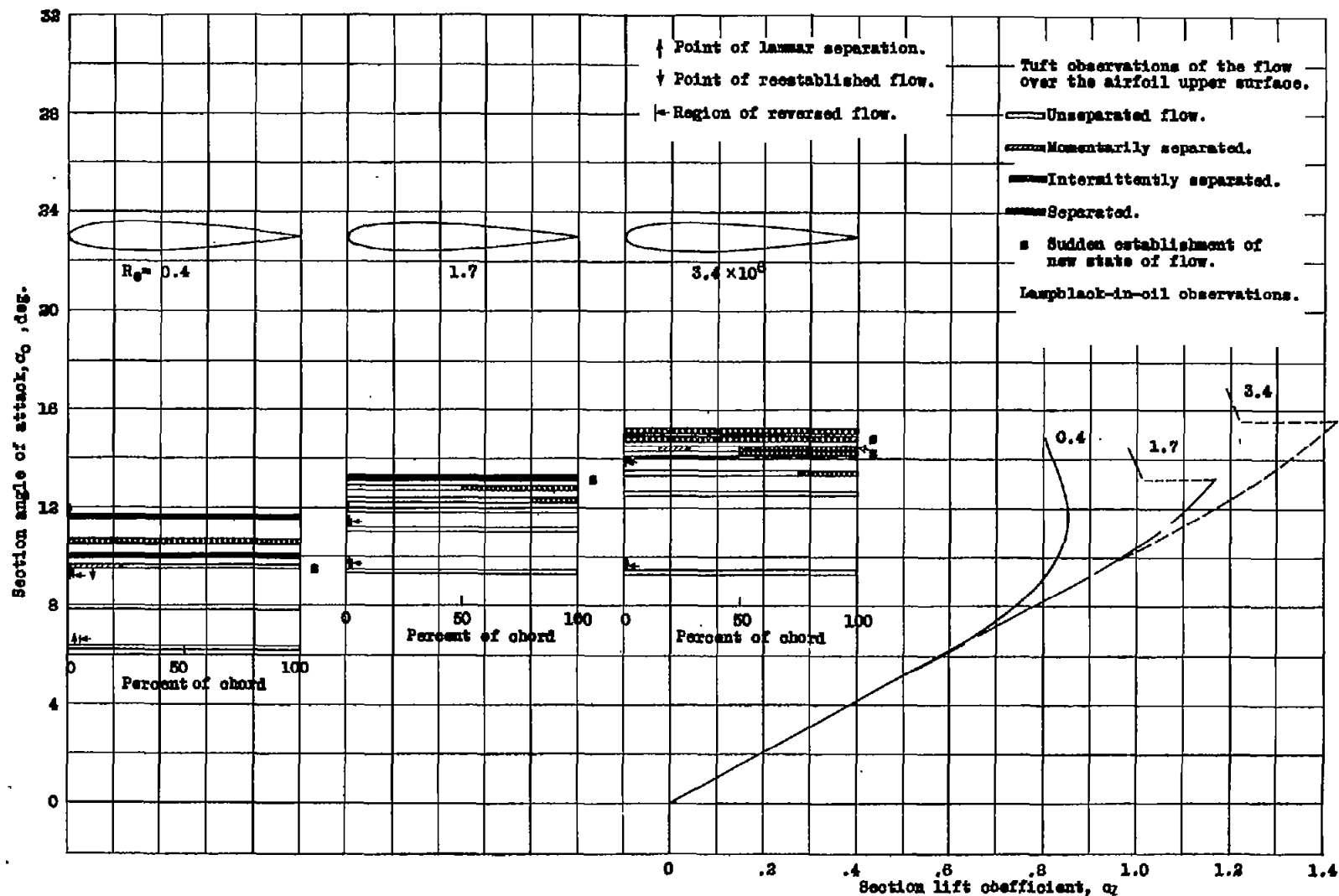
Figure 2.- Flow observations on the N.A.C.A. 0012 airfoil.
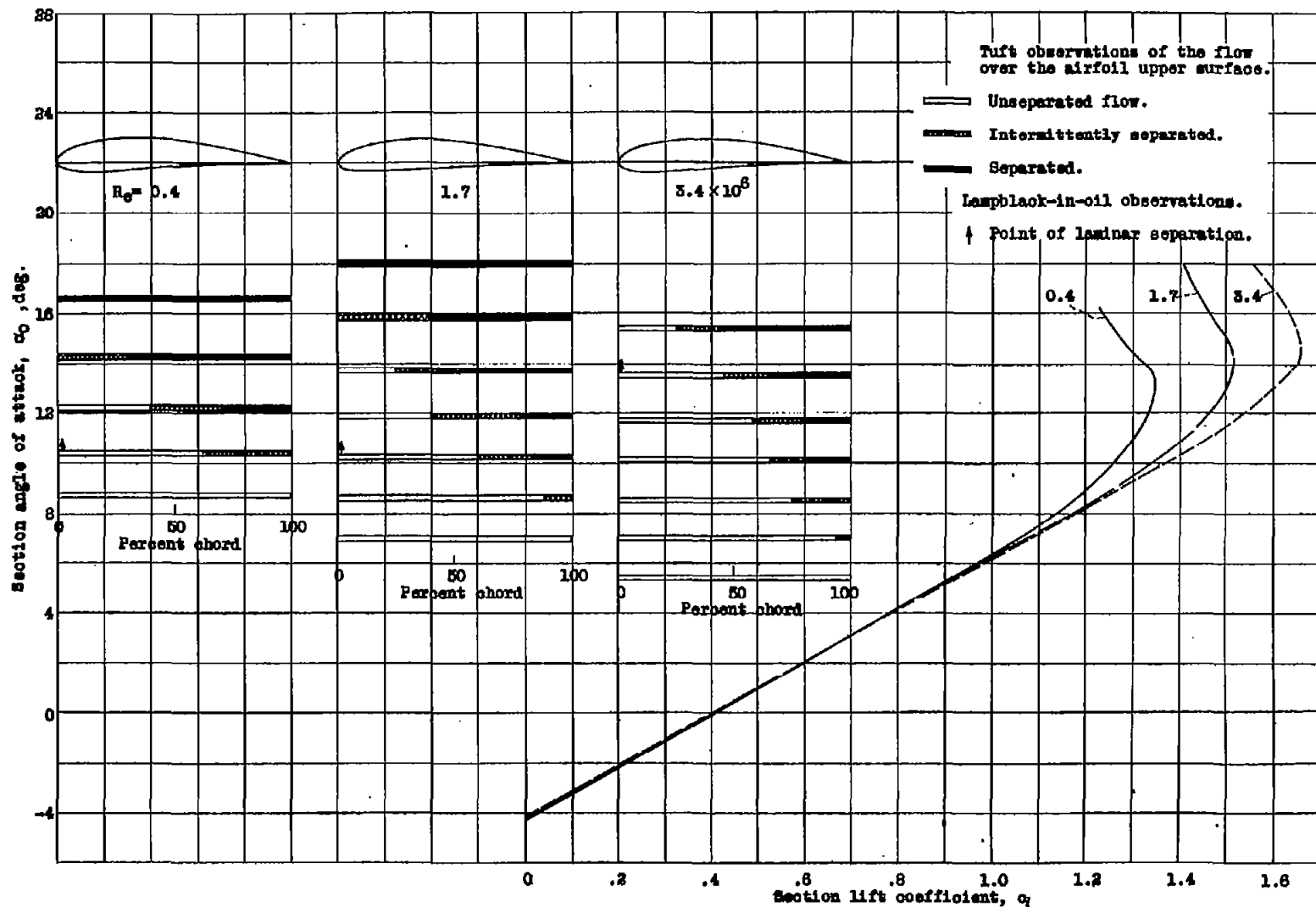
Figure 3.- Flow observations on the N.A.C.A. 4412 airfoil.

Fig. 3

RM SL8B 24

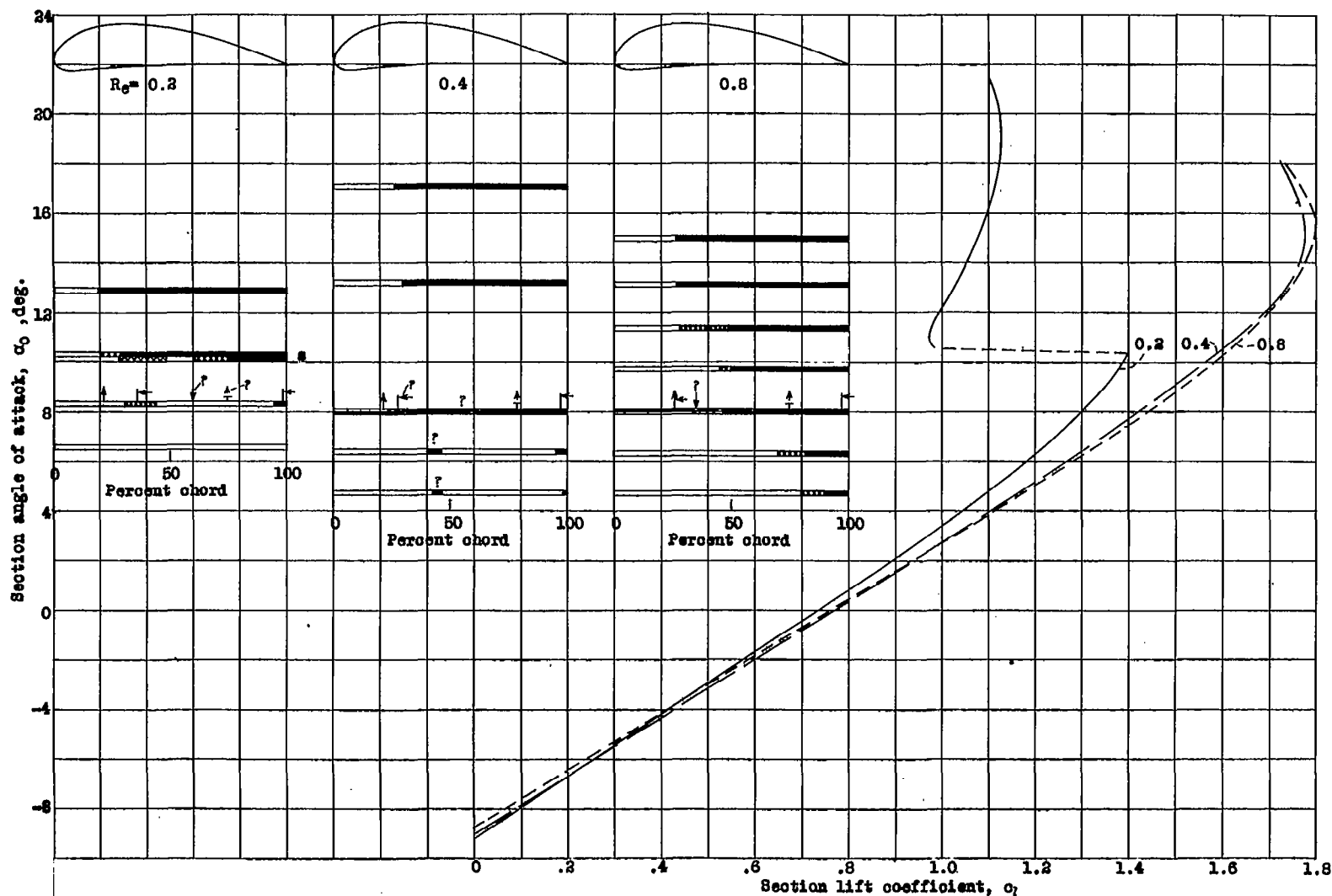Kampf + Feuder.

Wiler

Pennsiem.

Figure 4a.- Flow observations on the N.A.C.A. 8318 airfoil. (See figure 4b for key)
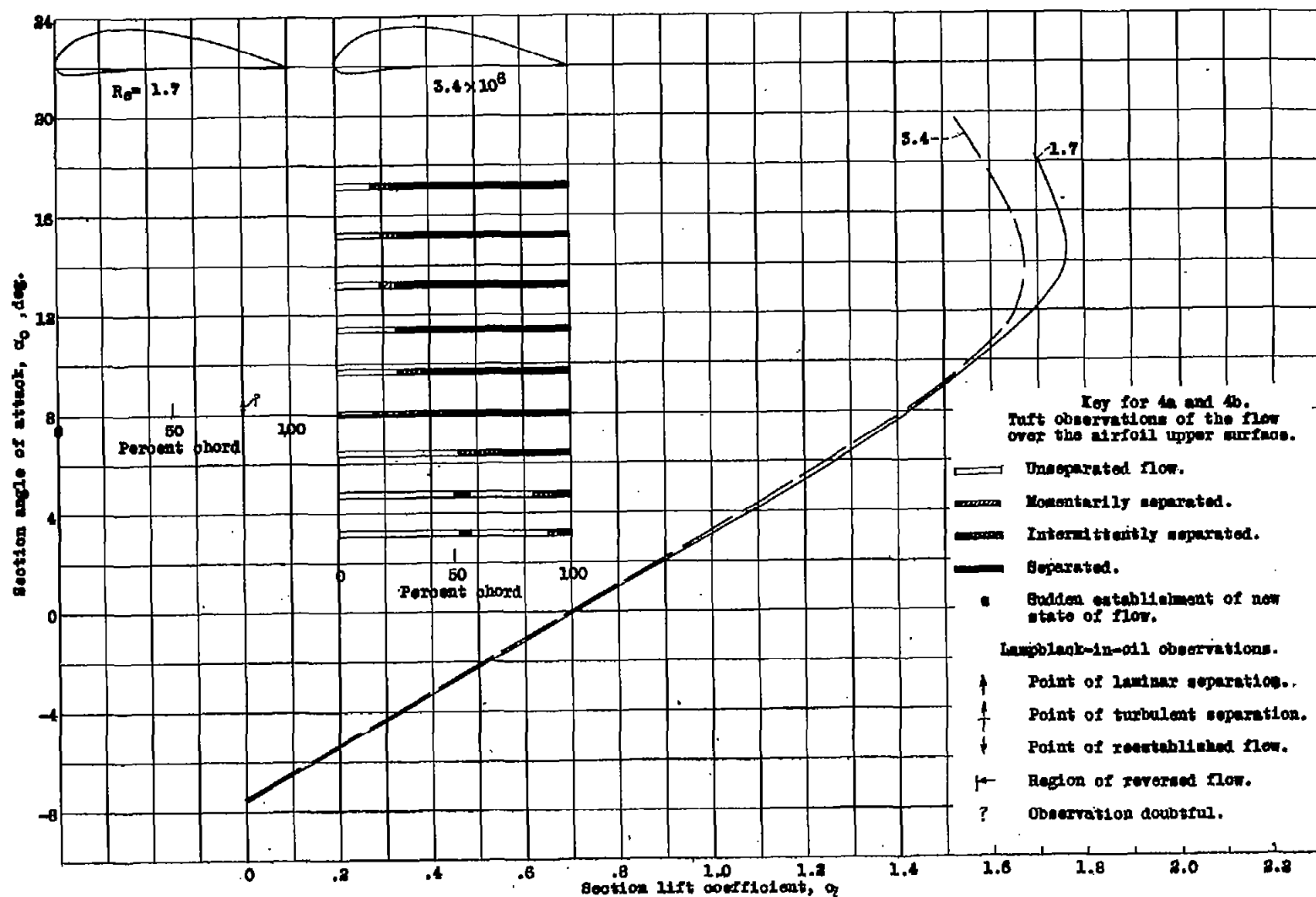
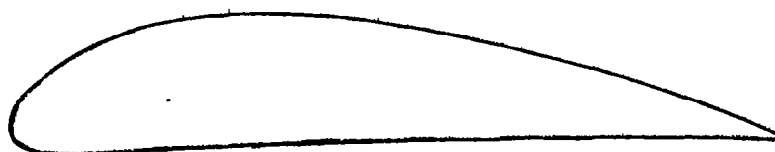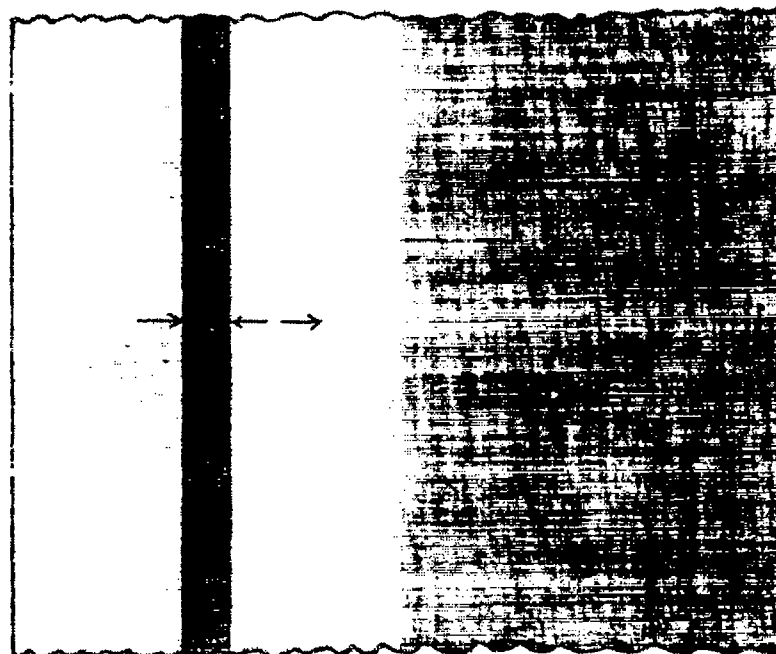Figure 4b.- Flow observations on the N.A.O.A. 8318 airfoil.

Figure 5a.- Sketch indicating general appearance
            of lampblack pattern on forward
portion of N.A.C.A. 8318 airfoil. Arrows show
direction of motion of lampblack.

Figure 5b.- Lampblack pattern on N.A.C.A. 8318 airfoil. Photograph of
            pattern; α_o , 8.3° , R_e , 200,000.